Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer, One Quarter Scale Prototype Thermal Testing

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The Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx) instrument has been proposed as NASA Small Explorer (SMEX) and Medium Explorer (MIDEX) missions designed to perform an all-sky near-infrared survey. The primary science objective of the SPHEREx instrument is the mapping and cataloging of data on galaxy red shifts and absorption spectra. The SPHEREx instrument utilizes a linear variable band pass filter to provide discrete spectral coverage of the 0.75 to 5.0 µm range. The nominal on-orbit mission lifetime for the instrument is two years with continuous primary science imaging. The SPHEREx instrument will be placed in a near-circular LEO sun-synchronous terminator orbit with a mean altitude of 600 km, and solar beta angles ranging from 59° to 90°. A passive V-groove radiator cooling system was selected for the SPHEREx instrument. This design was chosen for its simplicity and lack of vibration. It includes five radiator stages with the coldest two stages providing temperatures below 80K and 55K for the 2.5µm and 5.3µm detectors respectively. A one quarter scale thermal prototype was constructed to characterize the performance of the SPHEREx thermal control subsystem. This prototype was directly derived and scaled from the current flight design, and accurately replicates all heat flow paths at scale. The prototype was tested in two bounding hot flight-like environments in the Cryogenic Systems Engineering, Advanced Thermal Technology Lab at NASA's Jet Propulsion Laboratory. Following testing, a previously developed one quarter scale thermal model was correlated to the two conditions seen in test. The resultant correlated model is able to predict the prototype test temperatures to within 1K for all critical radiator stages. An overview of the thermal control design approach, the test configuration, and test and correlation results are presented.

Nomenclature

FPA	=	Focal Plane Array
GM	=	Gifford-McMahon
JPL	=	Jet Propulsion Laboratory
JWST	=	James Webb Space Telescope
Ka-Band	=	Electromagnetic energy that ranges in frequency from 26.5 to 40 GHz
LN2	=	Liquid Nitrogen
MIDEX	=	Medium Explorer
MLI	=	Multi-Layer Insulation
OBA	=	Optical Bench Assembly
S-Band	=	Electromagnetic energy that ranges in frequency from 2 to 4 GHz
SMEX	=	Small Explorer
SPHEREx	=	Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer
SPIRIT	=	Space Infrared Interferometric Telescope

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I. Introduction and Background

The Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx) instrument was proposed by NASA's Jet Propulsion Laboratory (JPL) as both NASA Small Explorer (SMEX) and Medium Explorer (MIDEX) missions. Designed to perform an all-sky near-infrared survey, with a nominal two year on-orbit mission lifetime, the SPHEREx instrument will be placed in a near-circular LEO sun-synchronous terminator orbit with a mean altitude of 600 km. Solar beta angles will range from 59° to 90°[1].

The bus attitude control system is required to maintain sun and earth avoidance constraints to keep the spacecraft +Z axis > 91° from the sun and < 35° from local zenith to prevent solar and earth illumination of the instrument. The SPHEREx instrument employs a passive V-groove radiator thermal control subsystem to meet the project's combined cost, mass and stability requirements. Note that the V-groove radiator was invented at JPL by Ray Garcia[2], and further refined into a mature technology by JPL's Steve Bard and others[3-6]. The V-groove radiator is a mature space qualified technology that has flown on significant science missions such as Planck[7].

The SPHEREx V-groove based thermal control subsystem design was chosen for its simplicity and lack of vibration. It includes five radiator stages with the coldest two stages providing temperatures below 80K and 55K for the 2.5µm and 5.3µm detectors respectively[*]. The radiator stages include the focal plane radiator (cooling the 5.3µm detector) the OBA or telescope body (cooling the 2.5µm detector) as well as inner, mid and outer V-groove radiator stages.

Sidecar electronics are interfaced with the intermediate or mid V-groove radiator and must be kept below 200K. Figure 1 shows the general arrangement of the SPHEREx instrument and its thermal control subsystem. The deployed instrument measures approximately 2.9m x 1.4m.

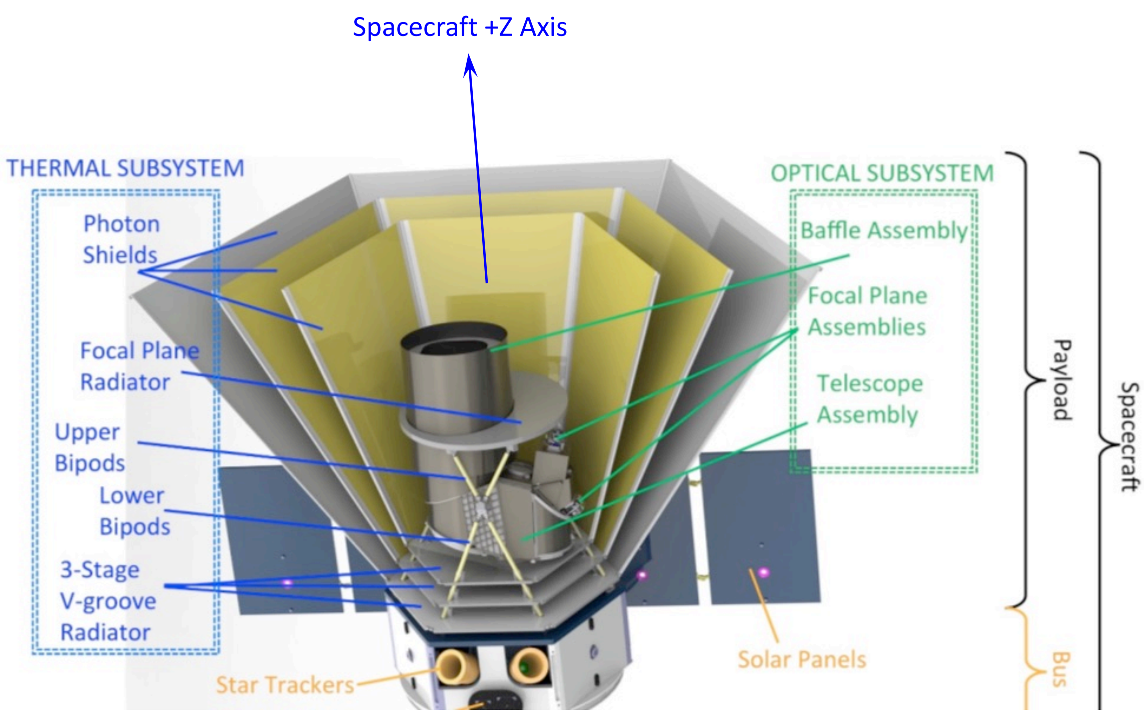

Figure 1. SPHEREx Instrument and Thermal Control Subsystem.

II. Instrument Thermal Control Subsystem Detail

The SPHEREx thermal control subsystem arrangement is shown in Figure 2. The heart of the system employs three V-groove radiator stages. The V-groove radiator stages function to sequentially extract heat away from the instrument support structure and instrument cables, and radiatively reject that heat to deep space. Additionally, the mid V-groove radiator rejects heat generated by the Sidecar electronics. Each radiator is oriented at an angle

[*] http://spherex.caltech.edu/

relative to adjacent radiators in order to induce heat energy to reflect out of the system. The V-groove radiators are covered with a specularly reflecting, low infrared emissivity coating.

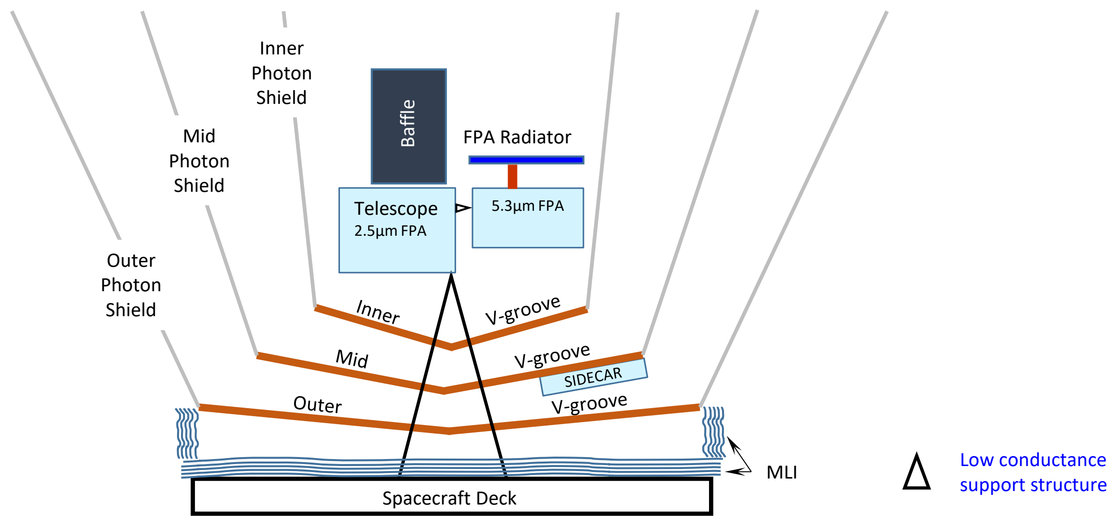

Figure 2. SPHEREx Thermal Control Subsystem Arrangement.

Deployable photon shields work in conjunction with each V-groove radiator stage. The photon shields, shield the instrument from illumination by the sun and earth, and isolate the instrument from the external environment. They also help to direct heat energy emitted by the V-groove radiators to deep space. Like the V-groove radiators, the photon shields are oriented at angles relative to adjacent shields to induce heat to reflect out of the system. The inner and mid photon shields have a specularly reflecting, low infrared emissivity surface coating on both sides. The outer photon shield also uses a specularly reflecting, low infrared emissivity surface coating on its internal surface. However, it uses a low solar absorptivity, high infrared emissivity coating on its outer surface, so that it will function as a net heat rejecter when illuminated by the sun. Note that the photon shields connect to their associated V-groove radiators through deployment hinge assemblies at the base of each photon shield strut.

The telescope body acts as the fourth radiator stage, cooling the 2.5µm detector to < 80K. A black, high infrared emissivity coating is used on the telescope body to enhance heat rejection. The fifth and coldest stage of the SPHEREx thermal control subsystem is the focal plane array (FPA) radiator, which keeps the 5.3µm detector below its 55K limit. The FPA radiator is of an open-cell honeycomb design, which is covered with a high infrared emissivity black coating. The 5.3µm detector is connected to the FPA radiator via a highly conductive, flexible thermal strap.

The instrument support structure utilizes a triple bipod arrangement constructed from thin walled, low thermal conductivity composite materials. This arrangement helps to conductively isolate the instrument and minimize the heat energy being transferred through the structure. Instrument cables are routed up the bipod structure and thermally grounded at each V-groove radiator stage.

Multi-layer insulation (MLI) is used to radiatively isolate the instrument from the top deck of the spacecraft bus, and prevent the earth and sun from illuminating the underside of the outer V-groove radiator.

III. Scale Prototype Testing

The SPHEREx thermal design was validated by testing a one quarter scale prototype of the flight thermal control subsystem. This work was done as part of the Small Explorer proposal effort. The subscale approach overcomes the limitations of facility size and prohibitive costs seen with many full scale tests of passively cooled cryogenic instruments. The approach for the SPHEREx test is similar to that used by The Space Infrared Interferometric Telescope (SPIRIT)[8] and the James Webb Space Telescope (JWST)[9].

A. Test Article

The SPHEREx subscale thermal prototype is directly derived from the full scale flight thermal control subsystem design. Geometry is accurately replicated at 1/4 scale, flight grade materials are used throughout, and all surface finishes are consistent with the flight design. Since radiative loads scale with area, a 1/4 geometric scaling produces a 1/16 reduction in environmental radiative loads and radiative exchange. All dissipations and conduction paths were also scaled to 1/16 for consistency. As a result, the prototype replicates the temperatures and relative heat flows seen in the flight system. However, due to material availability and limitations in machining processes, bipod wall thicknesses were thicker than that for the target 1/16 conductance scaling. In fact, the conductance through the prototype bipods exceeds the expected combined conductances of both the flight bipods and flight cables at a 1/16th scaling. Because of the bipod conductance, there is some difference between prototype temperature performances as compared to the flight configuration. In other words, the better isolated flight system will outperform the prototype from a temperature standpoint. Note that the test item bipods were used to simulate the conductance of both the bipods and flight instrument cabeling in the test article.

The current flight design calls for all three V-groove radiators to be made from honeycomb panels with aluminium face sheets. To match the through-the-thickness conductance of the flight V-groove radiators at 1/16 scale, the prototype utilizes V-groove radiators machined from a low conductance polymer (Figure 3). In order to match the 1/16 lateral conductance of the flight V-groove radiators, these polymer radiators were coated with a metallic coating to the appropriate thickness. The V-groove radiators were then covered with a specular, low emissivity polymer film to achieve the required infrared emissivity and specularity (Figure 4). A heater element was embedded into the mid V-groove radiator to simulate the dissipation of the Sidecar electronics.

Figure 3. Uncoated V-groove Radiator Blanks.

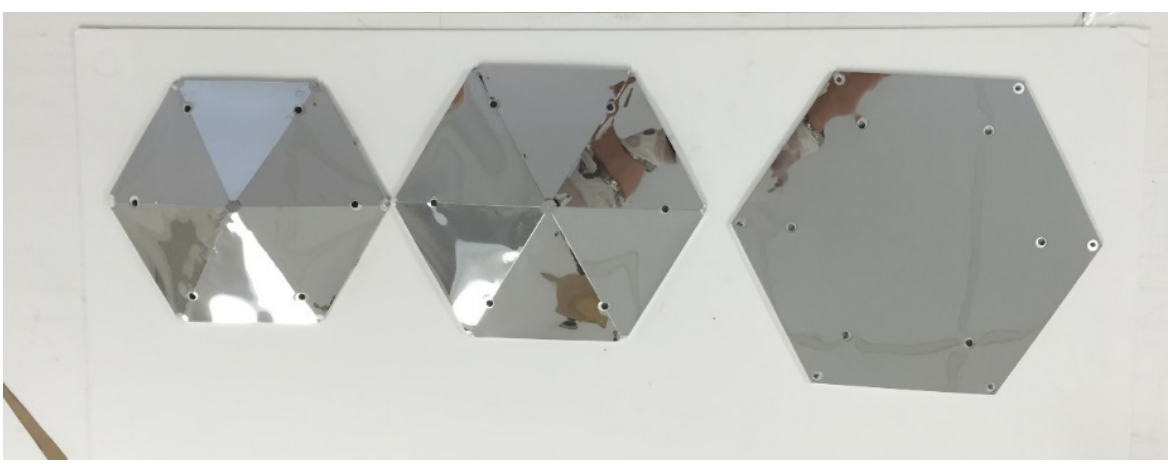

Figure 4. Completed V-groove Radiators with Specular Low Emissivity Covering.

Inner and mid prototype photon shields were made from flight grade polymer film with a specular, low emissivity coating on both sides. Outer photon shields utilize an inner layer made from polymer film with a specular, low emissivity coating on its inner side. The outer layers of the outer photon shields are made from a low solar absorptivity, high infrared emissivity polymer film. To simulate external radiative heat loads, multi-zoned heater elements were placed between the inner and outer layers of the outer photon shields (Figure 5). The heater elements were bonded to metallic substrates to minimize lateral temperature gradients. The heater zones within the outer photon shields were arranged so that heat loads from the earth and sun, as well as the spacecraft bus and solar arrays are accurately simulated. Figure 6 shows the relative location of each of the outer photon shield heater zones.

Figure 5. Multi-Zoned Photon Shield Heaters.

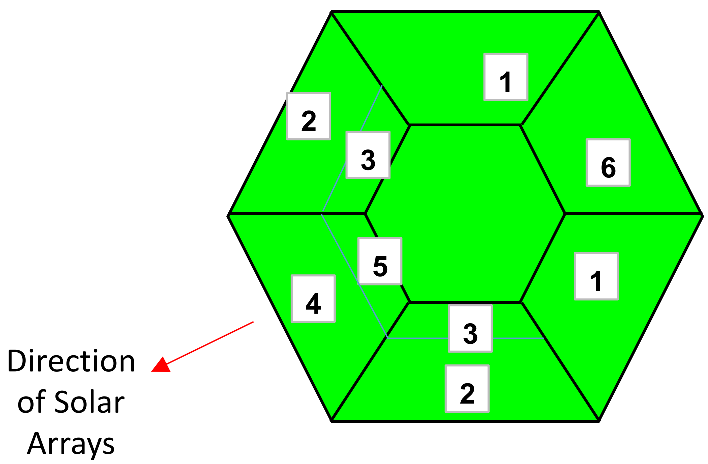

Figure 6. Outer Photon Shield Heater Zones, Viewed from the Spacecraft +Z Direction

The telescope prototype (Figure 7) was machined from aluminum and painted with a thick coating of high emissivity black paint. A heater element was embedded within the telescope to simulate the dissipation of the 2.5µm detector assembly, and a diode temperature sensor was bonded adjacent to the heater. As in the flight design, the telescope baffle is covered with a shield made from a single layer polymer film with a low emissivity coating to minimize radiation exchange with the FPA radiator.

Figure 7. One Quarter Scale Telescope.

The FPA radiator was cut from open cell honeycomb. The honeycomb was then primed and painted with high emissivity black paint. After bonding the honeycomb to its base plate it was painted again, using a process that completely coats all surfaces within each cell. This ensures a coating of sufficient thickness to perform well over the expected operating temperature range. A heater element was then embedded into the radiator baseplate to simulate the dissipation of the 5.3μm detector assembly. A diode temperature sensor was bonded to the bottom side of the radiator baseplate. Finally, the radiator assembly was covered with a polymer film with a specular, low emissivity coating (Figure 8).

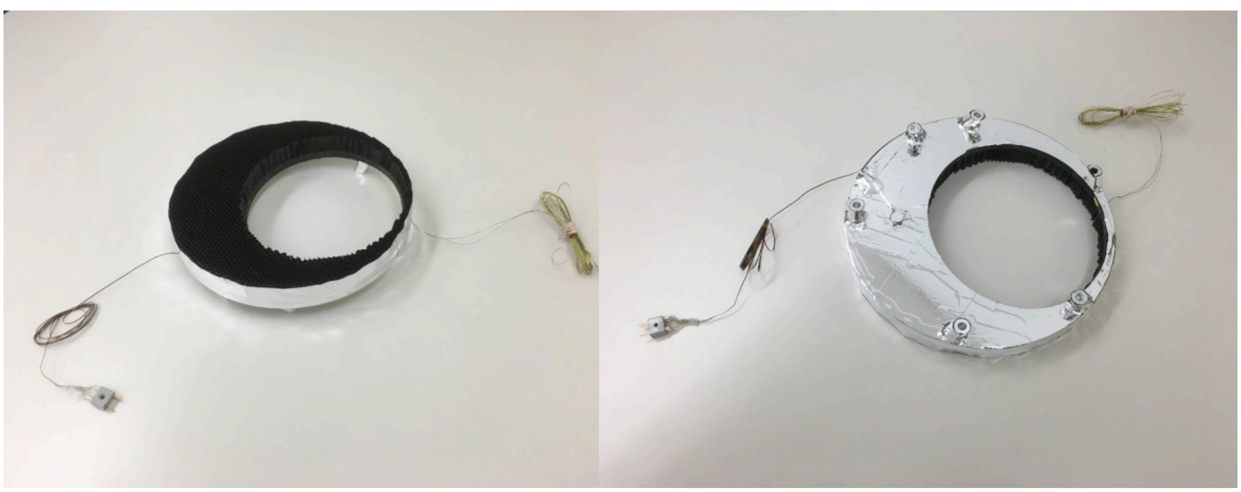

Figure 8. One Quarter Scale FPA Radiator Assembly.

Test item instrumentation consisted of Lakeshore Cryotronics DT-670 silicon diode temperature sensors[10]. As mentioned above, the telescope and FPA radiators each used a single temperature sensor. Low thermal conductivity leads were used on all diode temperature sensors to minimize parasitic conductive heat exchange.

Each V-groove radiator stage used three diode sensors. One located near a bipod penetration, one located near one of the outer edges, and the third located approximately 1/3 of the distance between a bipod and the center of the radiator as shown in Figure 9.

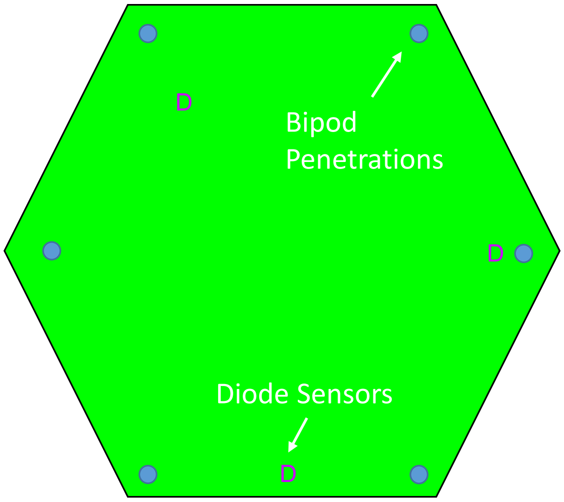

Figure 9. V-groove Radiator Temperature Sensor Locations.

Outer photon shield panels utilizes two diode temperature sensors per heater zone. The first sensor located near the center of the zone and the second located in one of the upper (spacecraft +Z) corners of the zone. The mid photon shield uses two temperature sensors on every other panel for a total of six sensors. The first sensor placed near the center of each panel with the second sensor near one of the upper (spacecraft +Z) panel corners. The inner photon shield uses a total of six sensors with three sensors placed at equal axial intervals along the centerlines of two opposing panels. Leads for all photon shield sensors were routed circumferentially along expected isotherms as shown in Figure 10. Sensors and leads were then covered with a specular, low emissivity coating to match the optical properties of the surrounding material. The complete instrumented photon shield assembly is shown in Figure 11.

Figure 10. Photon Shield Temperature Sensor and Lead Application.

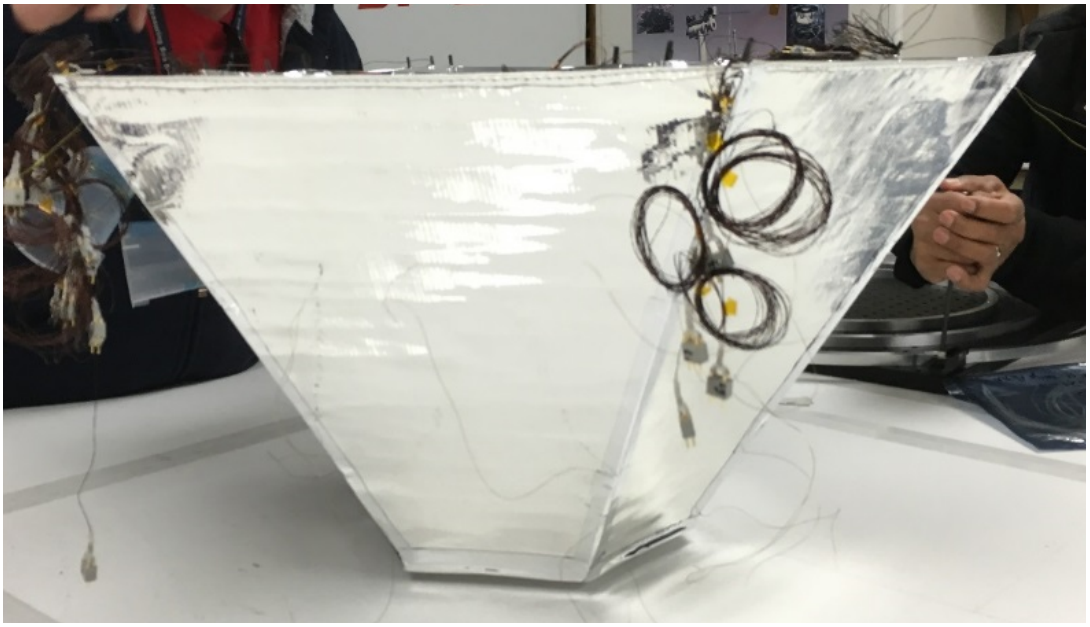

Figure 11. Instrumented Photon Shield Assembly.

B. Test Apparatus

The SPHEREx one quarter scale thermal prototype testing took place in the 48 inch (1.22m) thermal vacuum chamber in JPL's Advanced Thermal Technology Laboratory (Figure 12).

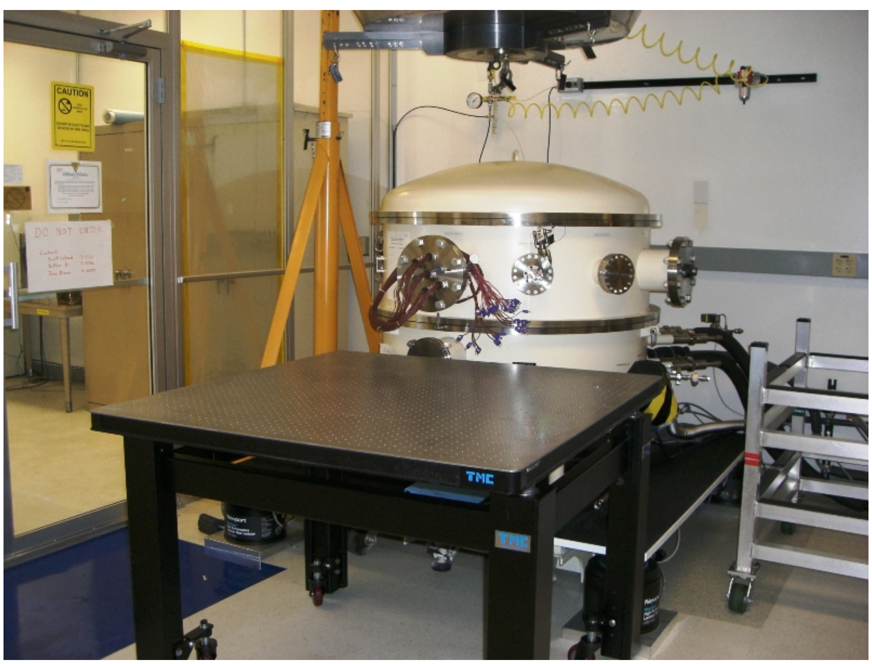

Figure 12. 48 inch (1.22m) Thermal Vacuum Chamber.

The thermal vacuum chamber was fitted with a dedicated liquid nitrogen (LN2) shroud (Figure 13). The shroud features separate liquid nitrogen circuits for the top, bottom and sidewalls. The inside of the shroud was painted with a thick coating of high emissivity black paint.

Figure 13. Liquid Nitrogen Shroud.

The thermal vacuum chamber was also fitted with a cold sink used to simulate deep space conditions (Figure 14). The cold sink was cut from open cell honeycomb. The honeycomb was primed and painted with high emissivity black paint, and bonded to an aluminum base plate. After bonding, the honeycomb was painted a second time using a process that completely coats all walls within each individual cell with high emissivity black paint. This process ensures a coating of sufficient thickness to perform well over the expected operating temperature range, in this case, down to 10K.

Figure 14. Cold Sink.

After painting, the cold sink was fitted with high conductance copper thermal straps for interfacing with a pair of high capacity Gifford-McMahon (GM) cryocoolers. A conformal MLI blanket was fitted to the outside of the cold sink to minimize radiant heat exchange with its surroundings (Figure 15).

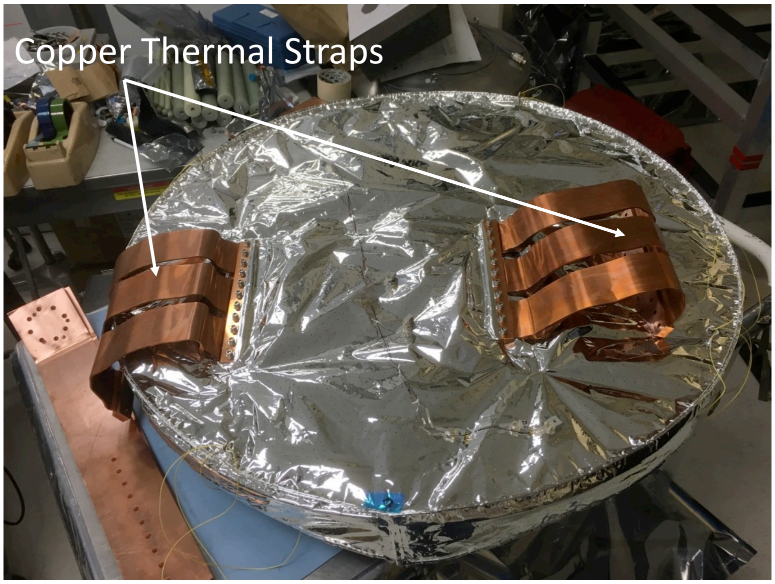

Figure 15. Completed Cold Sink.

Figure 16 shows the relative arrangement of the test apparatus and test item. Note that the cold sink was cooled during the test to approximately 10K via the high capacity GM cryocoolers.

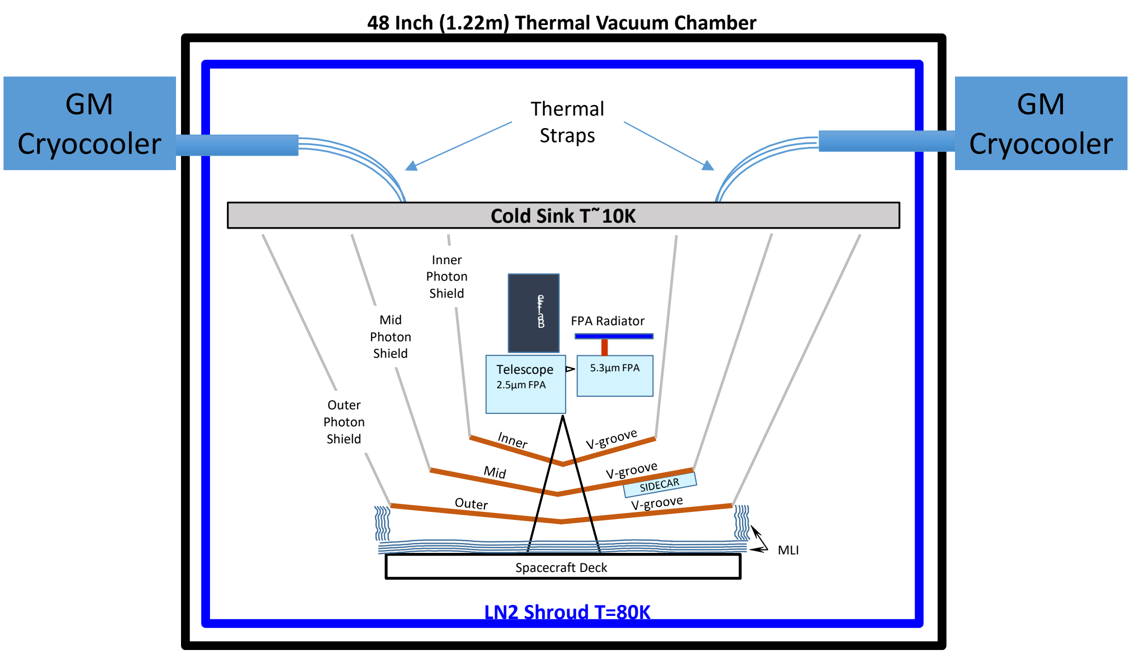

Figure 16. Arrangement of Test Apparatus Relative to Test Item.

Prior to installation of the prototype, a spacecraft simulator plate was positioned at the bottom of the LN2 cold shroud. The spacecraft simulator plate was constructed from aluminum and was fitted with heaters sufficient to maintain it near room temperature during testing (Figure 17). Flight design MLI was placed on the instrument facing side of the simulator plate to radiatively isolate it from the SPHEREx prototype. MLI was also used to close out the gap between the spacecraft bus simulator plate and the outer V-groove radiator.

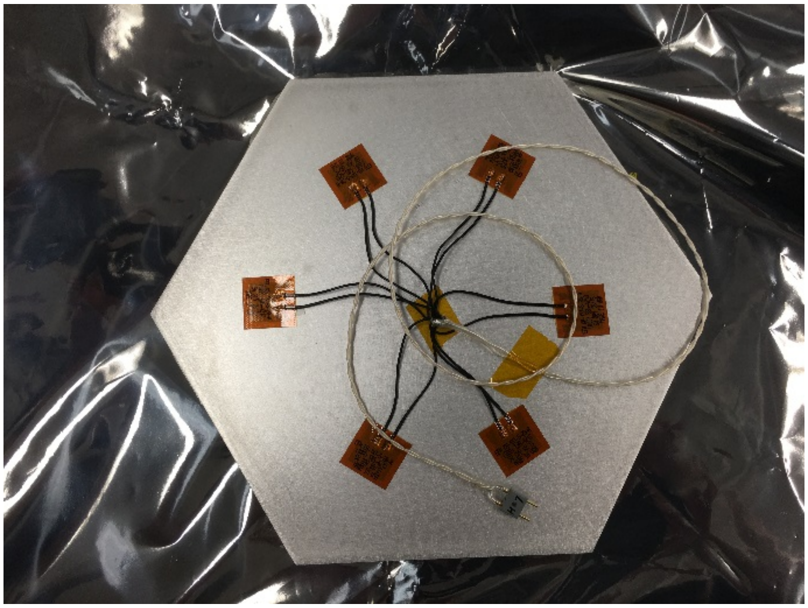

Figure 17. Spacecraft Simulator Plate.

After the test item was installed in the chamber, a web of low conductance cord was used to position the outer tips of each photon shield. The low conductance cord also served as a support system for instrumentation and heater leads (Figure 18). This approach allows the leads to equilibrate with the local radiation environment, minimizing the temperature gradient between the leads and their respective sense locations. This helped to minimize parasitic conductive heat exchange through the sensor leads.

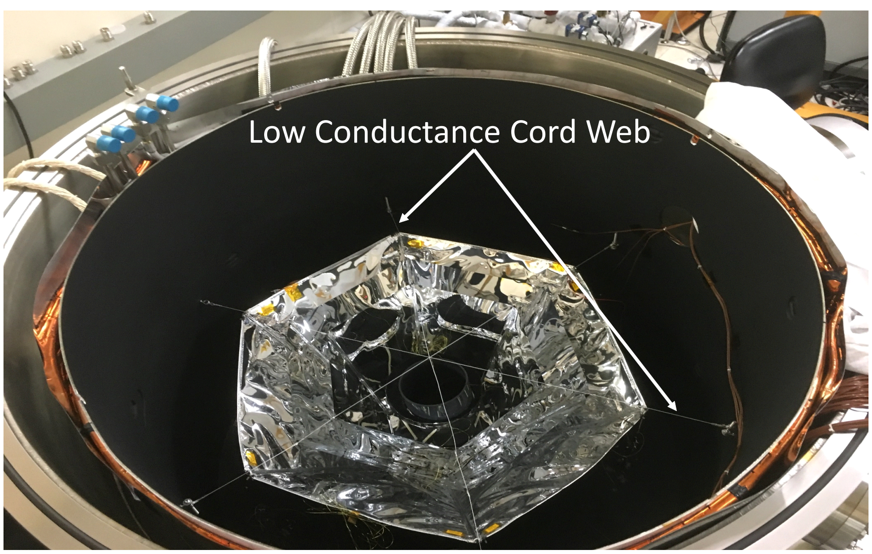

Figure 18. Low Conductance Cord Web.

Following installation of the instrument and the low conductance cord web, a closeout bib was placed around the edges of the outer photon shield panels to eliminate any unintended radiant energy leak paths between the outer photon shields and the edges of the cold sink. The bib was made from a disk of polymer film with a specular, low emissivity coating. Its diameter was slightly larger than the cold sink. A hexagon of the same shape as the outer photon shield edges was cut from the middle of the bib. The edges of the hexagon shaped cutout were then fixed to the outer edges of the outer photon shield. The installed bib is shown in Figure 19.

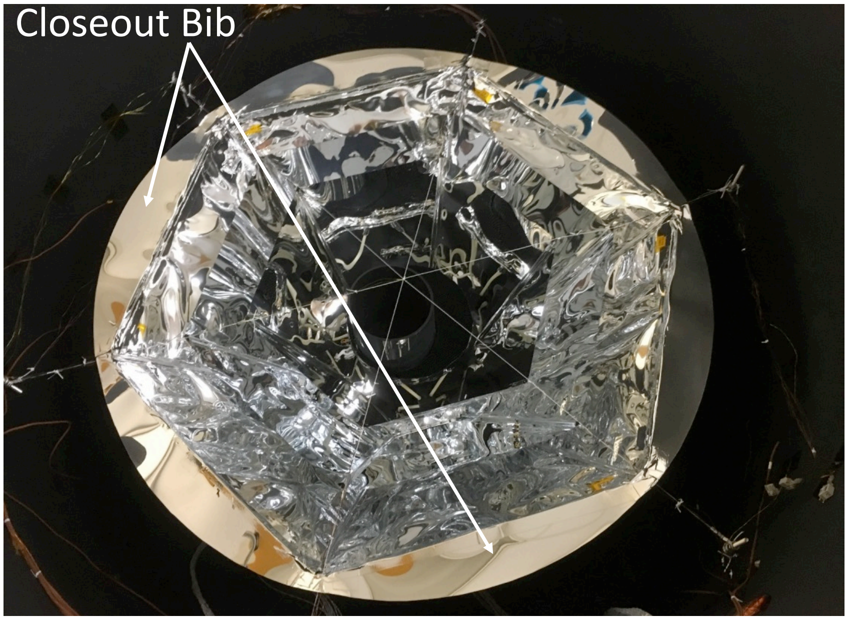

Figure 19. Closeout Bib.

Following installation of the closeout bib, the cold sink was lowered into place and shimmed to suspend by low thermal conductance cord approximately 4mm from the top edge of the outer photon shields. The outer edge of the close out bib was then fixed to the inside of the cold sink MLI to eliminate any radiant energy heat leaks.

C. Test Conditions

Two test conditions were run to steady state during the SPHEREx one quarter scale thermal prototype testing. The first condition was designed to be representative of the expected bounding hot flight case at 1/4 scale. The second test condition was similar to the first test condition; however, the heat load on the FPA radiator was increased until it reached a temperature of 60K. This was done to measure the available heat load margin on the FPA radiator. The specifics of each test case are given in Table 1 below.

Table 1. Test Conditions.

Test Condition	Description	Total Absorbed Photon Shield Heat Load (W)	Average Cold Target Temperature (K)	Average LN2 Shroud Temperature (K)	Simulated 2.5um FPA heat load (mW)	Simulated 5.3um FPA heat load (mW)	Simulated Sidecar heat load (mW)	Spacecraft Simulator Plate Temperature (K)
1	Bounding Hot Environment	66.3	10.9	84.2	1.0	1.0	55.00	286
2	FPA Radiator Power Margin	66.3	10.8	80.3	1.0	9.3	55.00	286

D. Test Results

Results from the test closely matched the expected performance of the flight system under similar environmental conditions. The prototype was able to maintain its FPA radiator below the 55K flight requirement for the 5.3µm detector. In addition, the telescope was well below the 80K requirement for the 2.5µm detector, and the mid conical panel met the 200K requirement for the Sidecar electronics with substantial margin. Test results are compared against these requirements in Table 2 below.

Table 2. Test Results.

Test	Radiator Stage	Test Measured Temperature [K]	Flight Requirement [K]
Test Condition 1 Bounding Hot Environment	Outer v-groove radiator panel	235.3	N/A
	Mid v-groove radiator panel	174.4	< 200
	Inner v-groove radiator panel	112.6	N/A
	Telescope Body (OBA)	61.4	< 180
	FPA Radiator	48.7	< 55
Test Condition 2 FPA Radiator Power Margin	Outer v-groove radiator panel	235.3	N/A
	Mid v-groove radiator panel	174.4	< 200
	Inner v-groove radiator panel	112.7	N/A
	Telescope Body (OBA)	61.9	< 180
	FPA Radiator	60.0	< 55

IV. Analytical Modeling

The flight thermal model was used as the foundation for the one quarter scale prototype test thermal model (Figure 20). After scaling to 1/4 of the flight size, and removing the solar arrays and bus, representations of the LN2 shroud, cold sink, and instrumentation were added to the test thermal model (Figure 21). Thermal Desktop[11] was used for both the flight and test thermal modeling and analysis.

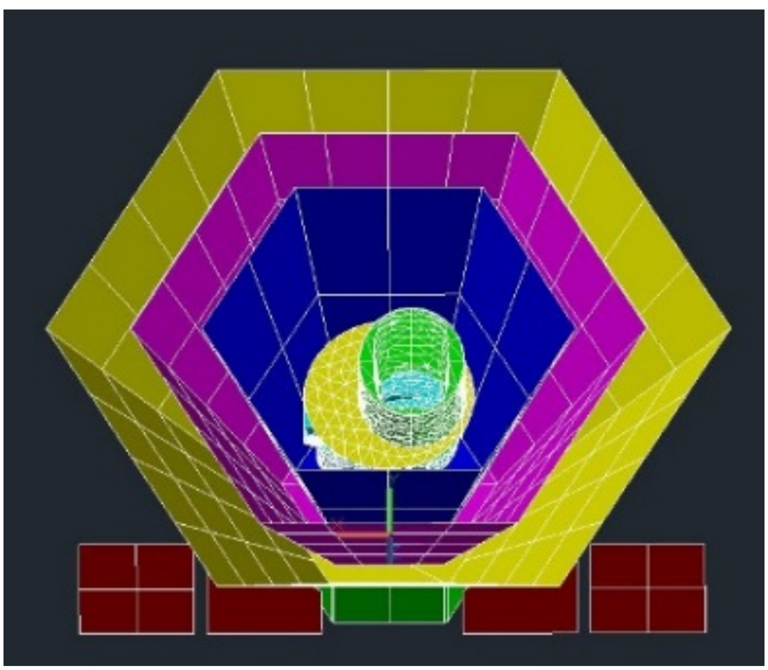

Figure 20. SPHEREx Flight Thermal Model.

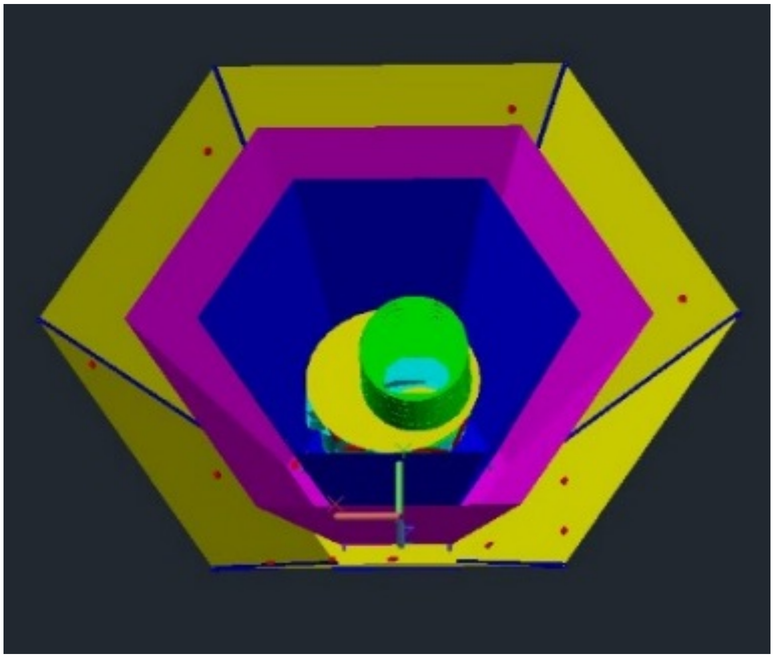

Figure 21. SPHEREx ¼ Scale Prototype Thermal Model.

Following testing, the test thermal model was successfully correlated to both test conditions, with all predictions agreeing to within 1K of test measurements. All applicable changes made to the test thermal model were then incorporated into the flight thermal model. A comparison of measured test temperatures and correlated model predictions is presented in Table 3.

Table 3. Comparison of Test Results to Correlated Model Predictions.

Test	Radiator Stage	Test Measured Temperature [K]	Correlated Model Prediction [K]	Applied Power [mW]
Test Condition 1 Bounding Hot Environment	Outer v-groove radiator panel	235.3	235.9	N/A
	Mid v-groove radiator panel	174.4	174.1	55.0
	Inner v-groove radiator panel	112.6	113.1	0
	Telescope Body (OBA)	61.4	61.0	1.0
	FPA Radiator	48.7	49.3	1.0
Test Condition 2 FPA Radiator Power Margin	Outer v-groove radiator panel	235.3	235.9	N/A
	Mid v-groove radiator panel	174.4	174.1	55.0
	Inner v-groove radiator panel	112.7	113.1	0.0
	Telescope Body (OBA)	61.9	62.8	1.0
	FPA Radiator	60.0	59.6	9.3

Detailed temperature maps of test conditions 1 and 2 are presented in Figures 22 through 25 below. Heat rejection maps for both test conditions follow in Figures 26 and 27.

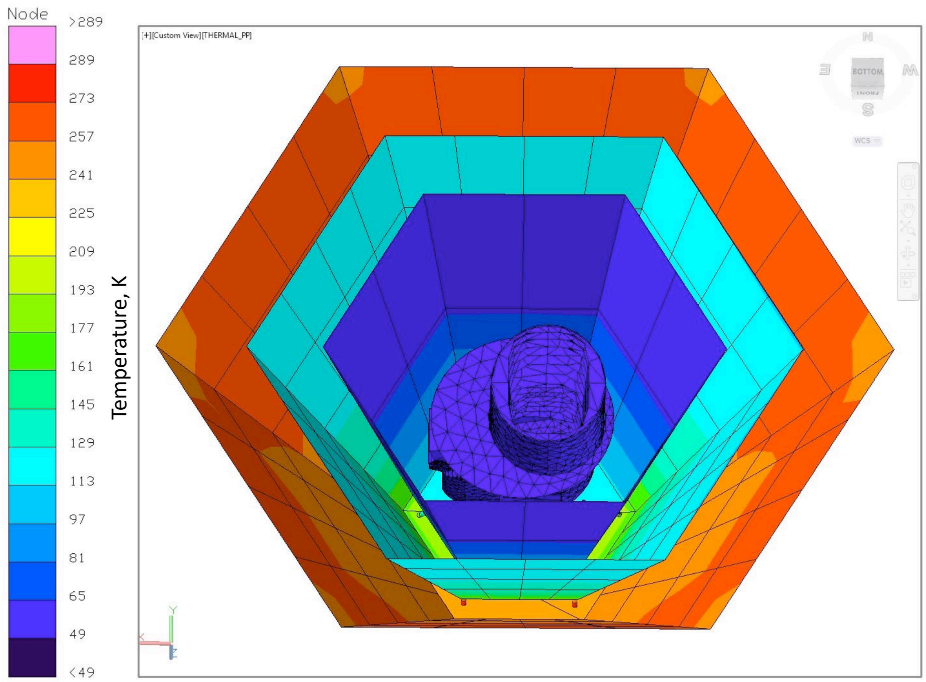

Figure 22. Test Condition 1 Instrument Temperature Map.

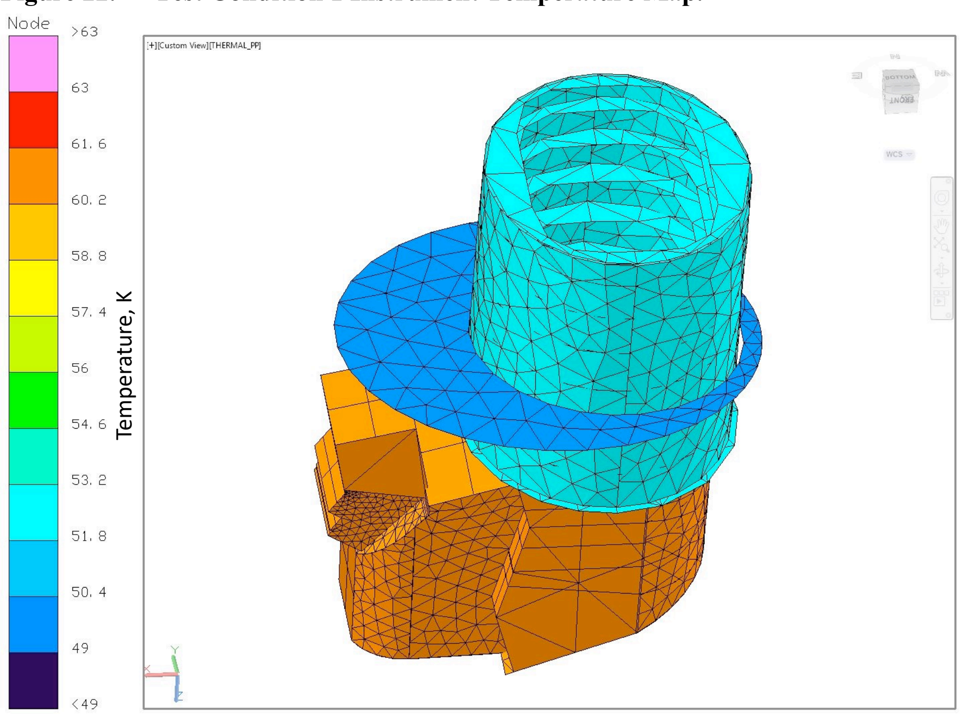

Figure 23. Test Condition 1 Telescope, Baffle and FPA Radiator Temperature Map.

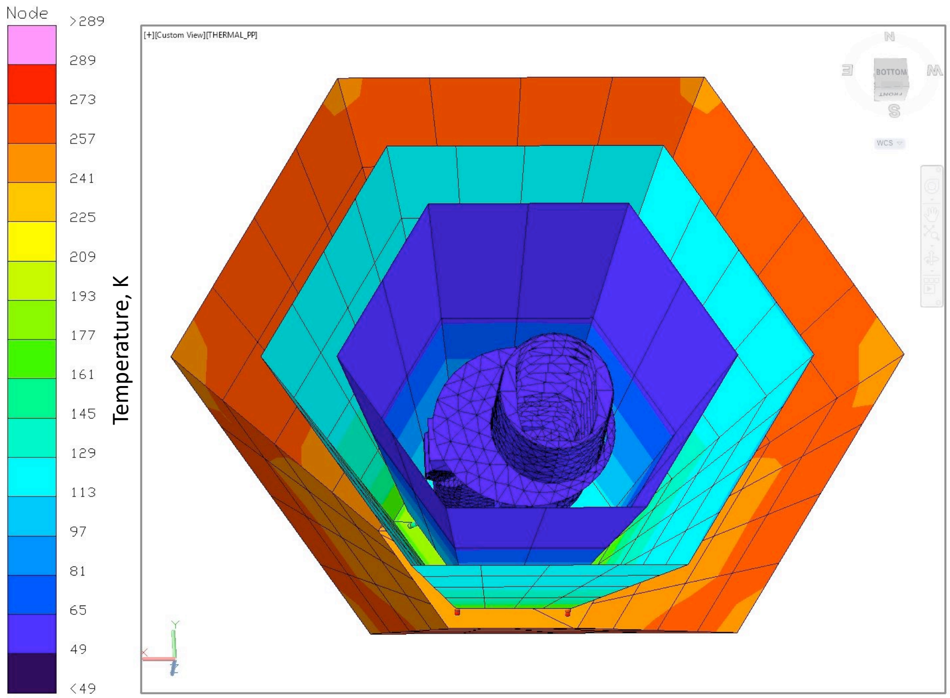

Figure 24. Test Condition 2 Instrument Temperature Map.

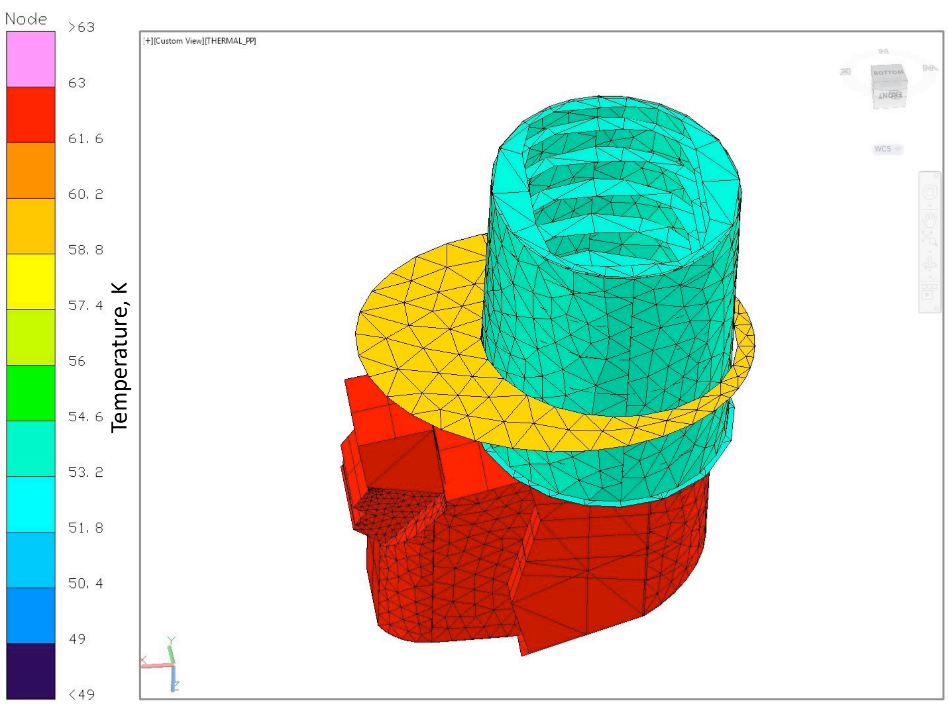

Figure 25. Test Condition 2 Telescope, Baffle and FPA Radiator Temperature Map.

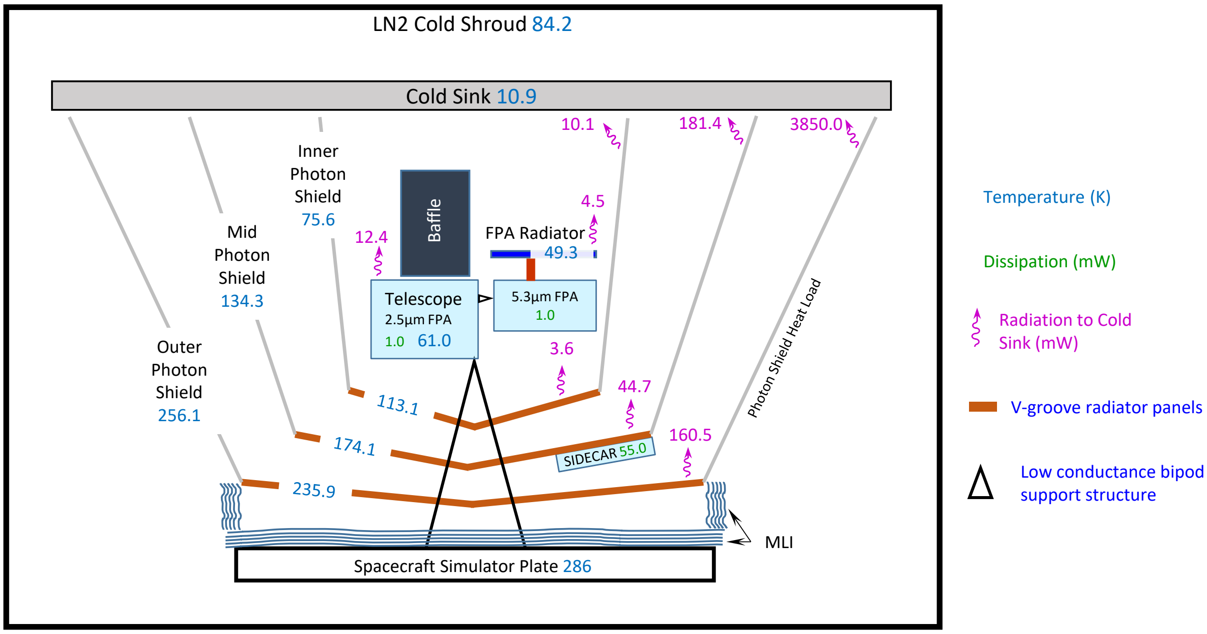

Figure 26. Test Condition 1 Heat Rejection Map.

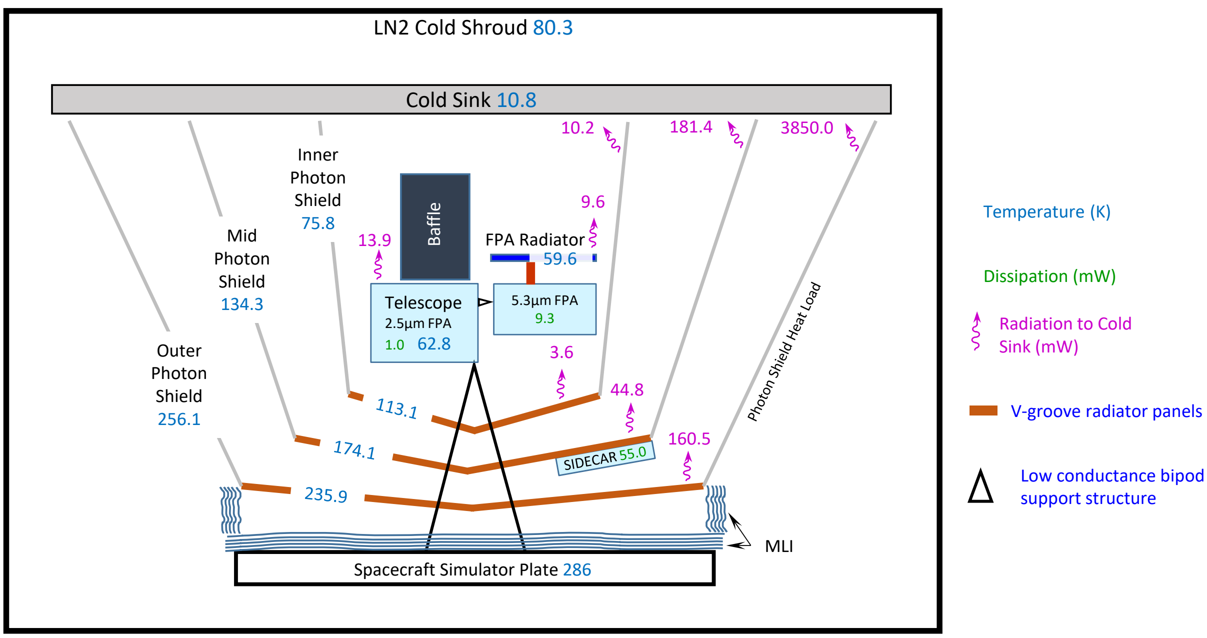

Figure 27. Test Condition 2 Heat Rejection Map.

V. Conclusions

Testing of the one quarter scale SPHEREx prototype thermal control subsystem has validated the performance of the SPHEREx thermal control subsystem in a simulation of the expected bounding hot flight environment. All thermal design requirements have been met, and FPA radiator heat load margin has been demonstrated to be significant.

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